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Sulphate

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MINISTRY OF ENVIRONMENT, LANDS AND PARKS

AMBIENT WATER QUALITY GUIDELINES FOR SULPHATE

OVERVIEW

DRAFT

Prepared pursuant to Section 2(e) of the
Environment Management Act, 1981

Approved: Nov 6/03

Date

Assistant Deputy Minister
Environment and Lands HQ Division

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Characteristic / Water Use	Dissolved Sulphate (as SO_4) mg/L
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** Alert level to monitor health of aquatic moss populations on an occasional basis

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1. to provide guidelines for the evaluation of data on water, sediment, and biota;
2. to provide guidelines for the establishment of site-specific ambient water quality objectives.

Ambient water quality objectives for specific waterbodies will be based on the guidelines and also consider present and future water uses, waste discharges, hydrology/limnology/oceanography, and existing background water quality. The process for establishing water quality objectives is more fully outlined in "Principles for Preparing Water Quality Objectives in British Columbia", copies of which are available from Water Quality Section of the Water Management Branch.

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- Raw drinking, public water supply and food processing*
- Aquatic life and wildlife
- Agriculture (livestock watering and irrigation)

* The guidelines apply to the ambient raw water source before it is diverted or treated for domestic use. The BC Ministry of Health regulates the quality of purveyed water.

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- Recreation and aesthetics**
- Industrial (water supplies)

The guidelines are set after considering the scientific literature, guidelines from other jurisdictions, and general conditions in British Columbia. The scientific literature gives information on the effects of toxicants on various life forms. This information is not always conclusive because it is usually based on laboratory work that, at best, only approximates actual field conditions. To compensate for this uncertainty, guidelines have built-in safety factors that are conservative but reflect natural background conditions in the province.

The site-specific water quality objectives are, in most cases, the same as guidelines. However, in some cases, such as when natural background levels exceed the guidelines, the objectives could be less stringent than the guidelines. In relatively rare instances, for example if the resource is unusually valuable or of special provincial significance, the safety factor could be increased by using objectives which are more stringent than the guidelines. Another approach in such special cases is to develop site-specific guidelines by carrying out toxicity experiments in the field. This approach is costly and time-consuming and therefore seldom used.

Guidelines are subject to review and revision as new information becomes available, or as other circumstances dictate.

** Guidelines relating to public health at bathing beaches are the same as those used by the Ministry of Health which regulates the recreation and aesthetic use.

INTRODUCTION

Sulphur is a non-metallic element that occurs naturally in numerous minerals, including barite ($BaSO_4$), epsomite ($MgSO_4 \cdot 7H_2O$), and gypsum ($CaSO_4 \cdot 2\ H_2O$). Hexavalent sulphur combines with oxygen to form the divalent sulphate ion (SO_4^{2-}). The reversible reaction between sulphide and sulphate in the natural environment is often referred to as the "sulphur cycle."

Natural sources of sulphur include volcanoes, decomposition and combustion of organic matter, and from sea salt over the oceans. Particles of sea salt formed by the breaking of myriads of bubbles are an important source of atmospheric sulphate. The atmosphere is the main vehicle for transport of sulphur from various sources.

Sulphates are discharged into the aquatic environment in wastes from industries that use sulphates and sulphuric acid, such as mining and smelting operations, kraft pulp and paper mills, textile mills and tanneries. Iron sulphides (e.g., FeS) may be exposed to water and atmospheric oxygen by mining or rock excavation, producing sulphuric acid, which contributes sulphate to ground and surface surface waters. Sulphates are also released during blasting and the deposition of waste rock in dumps at metal mines. This is known as acid rock drainage and is a significant source of sulphate generation in British Columbia. The burning of fossil fuels is also a major source of sulphur to the atmosphere. Most of man's emissions of sulphur to the atmosphere (about 95%) are in the form of SO_2. Sulphate fertilizers are also a major source of sulphate to ambient waters.

Sulphate concentrations typically range between about 2 and 30 mg/L for most lakes and rivers in British Columbia. Although, some lakes in the Cariboo Region and in Richter Pass near Osoyoos have particularly high natural sulphate levels in the thousands of mg/L. Seasonal fluctuations in dissolved sulphate concentrations are obvious in most rivers, with low concentrations during freshet and elevated concentrations during winter low flows.

Seawater typically contains about 2700 mg/L sulphate and it has been estimated that about 1.7 million tonnes of sulphate are added annually to the Canadian atmosphere from sea spray.

A few studies have reported sulphate toxicity to some aquatic organisms, including some fish and aquatic mosses at concentrations at or below 100 mg/L SO_4. However, there was some question as to the reliability of these data for a number of reasons such as poor laboratory test procedures, failure to report crucial test procedure information, or calculation errors.

In a recent series of bioassays performed specifically for this review, the lowest SO_4 effect level reported was 205 mg/L to a species of freshwater invertebrate in soft water.

Sulphate water quality guidelines were not considered necessary for water uses other than those recommended here.

RECOMMENDED GUIDELINES

THESE GUIDELINES are based on a comprehensive review of the available toxicological data for sulphate compiled in the Technical Appendix and are designed to suit B.C. conditions. The recommended B.C. Guidelines are summarized in Table 1.

1. DRINKING WATER SUPPLY

A concentration of ≤ 500 mg/L sulphate in water to be used for drinking is adopted from the B.C. Ministry of Health and Health Canada recommended drinking water guideline for sulphate as it is dispensed at the consumer's tap. This is an aesthetic objective based on taste considerations. Health Canada also advises that concentrations exceeding 500 mg/L may cause a laxative effect in some individuals.

We adopt this same concentration as a drinking water quality guideline for ambient waters. Even with advanced water treatment (other than reverse osmosis), sulphate concentrations will not be reduced at the consumer's tap.

2. FRESHWATER AQUATIC LIFE

To protect freshwater organisms in British Columbia, a water quality guideline of 100 mg/L for dissolved sulphate, measured as SO_4, is recommended. This guideline is a maximum concentration that should not be exceeded at any time.

There is conflicting evidence over the sensitivity of aquatic mosses to sulphate. Therefore, it is recommended that for waterbodies with concentrations of dissolved sulphate that exceed 50 mg/L as a result of anthropogenic sources, the health of aquatic moss populations should be checked on an occasional basis.

RATIONALE

The guideline is based primarily on three studies which investigated the effects of sulphate on freshwater organisms. These are as follows:

i. One study reported 1-, 2-, 3-, and 4-d LC50's of 2000, 1000, 500, and 250 mg/L for SO_4, respectively, and LC0's (no effect) of 500, 100, 100, and 100 mg/L, respectively, for striped bass (*Morone saxitilus*) larvae.

ii. Unpublished data from a series of toxicity tests performed by the Pacific Environmental Science Centre (PESC) for B.C. Ministry Of Environment, Lands & Parks in 1996 showed that the amphipod, *Hyalella*, was sensitive to sulphate in soft water (25 mg/L as $CaCO_3$), but not in medium (100 mg/L as $CaCO_3$) to hard water (250 mg/L as $CaCO_3$). PESC reported 96-h LC50s for *Hyalella* in soft, medium and hard water of 205, 3711, and 6787 mg/L SO_4, respectively. A water quality guideline of 100 mg/L provides protection with a 2:1 safety factor in soft water, and a significantly greater safety factor in waters with greater hardness, which are more typical throughout B.C.

iii. A German study demonstated that a concentation of 100 mg/L SO_4 was toxic to the aquatic moss, *Fontinalis antipyretica*, a species which is known to be widely distributed throughout B.C. Toxicity of SO_4 to four other species of aquatic moss ranged from 100 to >250 mg/L. There are more recent data that conflict with these earlier data from the German study, but the sensitivity of the endpoint effect of the newer data is in question.

iv. There is some anecdotal evidence that elevated sulphate levels (average of 71 mg/L sulphate; range of 27.7 to 189 mg/L) can stimulate large sulphur bacteria growths, which can cover creek beds and result in significant changes to the macroinvertebrate community. Anecdotal evidence is not used to derive water quality guidelines due to the absence of scientific defensibility of such information. However, such information is worth noting to provide the impetus to stimulate the necessary future research into such observations.

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There is some evidence that increased water hardness ameliorates sulphate toxicity which may allow for a site-specific sulphate objective that is less stringent than the guideline recommended here. To adjust the guideline recommended here to take local conditions into consideration, the B.C. Ministry Of Environment, Lands & Parks publication, *"Methods for Deriving Site-Specific Water Quality Objectives in British Columbia and Yukon"* should be followed.

H.J. Singleton, R.P.Bio
Water Management Branch
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TECHNICAL REPORT • SULPHATE

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Sulphate Technical Report

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MINISTRY OF ENVIRONMENT, LANDS AND PARKS
PROVINCE OF BRITISH COLUMBIA

AMBIENT WATER QUALITY GUIDELINES FOR SULPHATE

Technical Appendix

H. Singleton, R.P.Bio
Water Quality Section
Water Management Branch
Victoria, B.C.

November, 2000

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1. INTRODUCTION

This document discusses the effects of sulphate on the various water use categories which may include drinking water, aquatic life, wildlife, livestock watering, irrigation, recreation and aesthetics, and industrial water supplies.

This document focuses primarily on the protection of aquatic life. Where applicable, or where sufficient information exists, guidelines are recommended to protect other water uses from the deleterious effects of sulphate. As part of this guideline development process, water quality standards, objectives, and guidelines and accompanying rationales from other jurisdictions are reviewed and their suitability for British Columbia waters are considered.

The need for water quality guidelines for sulphate in BC has been identified by regions over the desire of some BC mines to discharge sulphate at levels which exceed those that normally occur in natural freshwater systems. There are currently no water quality guidelines specified for sulphate in Canadian waters to protect environmental resources. Generally, sulphate is not believed to be particularly toxic to aquatic organisms, except at very high concentrations.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.1. SULPHATE IN WATER

Sodium, potassium, and magnesium sulphates are all readily soluble in water. Calcium sulphates are relatively less soluble than sodium, potassium, and magnesium sulphates, and are slightly more soluble in cold water than warm water, while barium and some other heavy metal sulphates are not (CRC Handbook of Chemistry and Physics, 50th Ed). Dissolved sulphate may be reduced to sulphide, volatilized to the air as hydrogen sulphide, precipitated as insoluble salt or incorporated into living organisms.

2.2. ANALYTICAL TECHNIQUES

Sulphate in aqueous solutions may be determined by ion chromatography using a conductivity detector; the detection limit for this method is about 0.05 mg/L (APHA, 1985).

3. OCCURRENCE IN THE ENVIRONMENT

3.1. NATURAL SOURCES

Sulphur is a non-metallic element that occurs naturally in numerous minerals, including barite ($BaSO_4$), epsomite ($MgSO_4 \cdot 7H_2O$), and gypsum ($CaSO_4 \cdot 2\ H_2O$). Hexavalent sulphur combines with oxygen to form the divalent sulphate ion (SO_4^{2-}). The reversible reaction between sulphide and sulphate in the natural environment is often referred to as the "sulphur cycle." Natural sources of sulphur include volcanoes, decomposition and combustion of organic matter, and from sea salt over the oceans. Particles of sea salt formed by the breaking of myriads of bubbles are an important source of atmospheric sulphate. The atmosphere is the main vehicle for transport of sulphur from various sources (Kellogg *et al.* 1972).

3.2. ANTHROPOGENIC SOURCES

Sulphates are discharged into the aquatic environment in wastes from industries that use sulphates and sulphuric acid, such as mining and smelting operations, kraft pulp and paper mills, textile mills and tanneries. Iron pyrite (FeS) may be leached from abandoned coal mines and the sulphide ions converted in surface waters to sulphates. Sulphates are also released during blasting and the deposition of waste rock in dumps at metal mines. This is a significant source of sulphate generation in British Columbia (Jarman, personal communication). The burning of fossil fuels is also a major source of sulphur to the atmosphere. Most of man's emissions of sulphur to the atmosphere (about 95%) are in the form of SO_2. Sulphate fertilizers are identified as a major source of sulphate to ambient waters (Kellogg et al. 1972).

3.3. SULPHATE CONCENTRATIONS IN RECEIVING WATERS

3.3.1. FRESHWATER

Sulphate concentrations in Canadian Lakes typically range from 3 to 30 mg/L according to Katz (1977). In a survey of river waters in western Canada, excluding the province of BC, sulphate concentrations ranged from 1 to 3040 mg/L; most concentrations were below 580 mg/L (Environment Canada, 1984). Dissolved sulphate data for BC freshwaters, collected for acid rain assessment (Phippen *et al.* 1996), and for the Canada-BC Water Quality Monitoring Agreement (BC MELP and EC, 1996a-ac) are compiled in Table 1. Mean concentrations range between about 2 and 30 mg/L for most lakes and rivers throughout the province. However, some lakes in the Cariboo Region and in Richter Pass near Osoyoos have unusually high natural sulphate levels in the thousands of mg/L (Warrington, personal communication). Seasonal fluctuations in dissolved sulphate concentrations are obvious in most rivers, with low concentrations during freshet and

elevated concentrations during the low winter flow periods as shown for the Bear River at Stewart BC (Figure 1). Also, in a study of rainfall-induced changes in chemistry of a British Columbia coastal creek, Whitfield *et al.* (1993) noted decreases in sulphate concentrations (1.7 to 1.0 mg/L and 1.9 to 1.5 mg/L) during two rainfall events. Concentrations returned to pre-storm conditions over a period of several days.

3.3.2. SEAWATER

Seawater contains about 2700 mg/L sulphate (Hitchcock, 1975) and it has been estimated that about 1.7 million tonnes of sulphate are added annually to the Canadian atmosphere from sea spray (Katz, 1977).

4. RAW DRINKING WATER

4.1. EFFECTS

Sulphate is a substance that occurs naturally in drinking water. The lethal dose for humans as potassium or zinc sulphate is 45 g. The reported minimum lethal dose in mammals is 200 mg/kg (Arthur D. Little Inc., 1971). Sulphate doses of 1000 to 2000 mg (14-29 mg/kg bw) can have a laxative effect on humans (McKee and Wolf, 1963) causing diarrhea, especially when switching abruptly from drinking water with low sulphate to drinking water with high sulphate concentrations (U.S. EPA, 1999). Water containing 1000 mg/L $MgSO_4$ acts as a purgative in normal humans, but concentrations below this are apparently physiologically harmless to the general population (McKee and Wolf, 1963; Arthur D. Little Inc., 1971). Humans are able to adapt to higher concentrations with time (U.S. EPA, 1985).

Dehydration has also been reported as a common side-effect in humans following the ingestion of large amounts of $MgSO_4$ or Na_2SO_4 (Fingl E., 1980).

The taste threshold concentrations for the most prevalent salts are 250-500 mg/L (median 350 mg/L) for Na_2SO_4, 250-900 mg/L (median 525 mg/L) for $CaSO_4$, and 400-600 mg/L (median 525 mg/L) for $MgSO_4$ (National Academy of Sciences, 1977). Concentrations of sulphate salts at which 50% of panel members considered the water to have an offensive taste were approximately 1000 and 850 mg/L for $CaSO_4$ and $MgSO_4$, respectively (Zoeteman, 1980).

4.2. GUIDELINES FROM THE LITERATURE

The Office of Water in the United States specifies a secondary maximum contaminant level (MCL) for sulphate of 250 mg/L in drinking water, based on aesthetic effects (i.e., taste and odour). This regulation is not a Federally enforceable standard, but is provided as a guideline for States and public water systems.

4.3. RECOMMENDED GUIDELINE

The aesthetic objective for sulphate of ≤ 500 mg/L in water to be used for drinking is adopted from the Guidelines for Canadian Drinking Water Quality (Health Canada, 1996), which has been accepted by the BC Ministry of Health[1] for application in British Columbia.

[1] The BC Ministry of Health regulates the quality of purveyed water.

4.4. RATIONALE

This drinking water objective for sulphate is based on taste considerations. Because of the possibility of adverse physiological effects at higher concentrations, it is also recommended that health authorities be notified of drinking water that contain sulphate concentrations in excess of 500 mg/L (Health Canada, 1996). Health Canada advises by footnote that there may be a laxative effect in some individuals when sulphate levels exceed 500 mg/L.

5. AQUATIC LIFE

The strategy used to derive a water quality guideline for sulphate to protect aquatic life was to assess the available aquatic toxicological data for sodium sulphate, magnesium sulphate and potassium sulphate which are soluble in water, and for calcium sulphate which is relatively insoluble. These compounds were chosen for assessment because of the innocuous nature of the cations, Na, Mg, K, and Ca, and their common occurrence in natural waters. The purpose of this assessment was to derive a guideline for SO_4 without masking by more toxic substances such as the copper in $CuSO_4$, or from acidity as in the case of sulphuric acid (H_2SO_4). In such cases the water quality guidelines for the more toxic copper or acidity should apply, and such data were not used in this assessment. However, the possibility of some toxic influence from the presence of the added cations (Na, Mg, K, and Ca) cannot be excluded.

Initially, the available toxicological data was screened for exotic species that should be excluded from the assessment such as brine shrimp (*Artemia salina*), bleak (*Alburnus alburnus*) and the harpacticoid copepod (*Nitocra spinipes*) which are brackish water inhabitants. While some species included in the data set are not indigenous to British Columbia waters, they were included as indicator species, to represent related taxonomic groups that may live in BC, but for which no data were available. The toxicity data for freshwater organisms were downloaded from the U.S. EPA on-line aquatic toxicological data base AQUIRE, as well as data from other sources. These data are summarized in Table 2 and converted from µg/L or molar Na_2SO_4, $MgSO_4$, K_2SO_4, and $CaSO_4$ to mg/L SO_4 to ensure that the data are comparable. On reviewing original key references, numerous data points in the AQUIRE database were found to be incorrect. The incorrect values were identified and replaced with the correct data from the original references where appropriate in Table 2.

Effect values >10 000 mg/L were deleted from the data set because, to derive a water quality criterion to protect aquatic life, the lower effect levels are the most critical. The tabulated data were screened for the more sensitive effect levels (below 1000 mg/L SO_4) and the original published studies were assessed to determine if they were appropriate to derive a guideline (i.e., no unusual confounding factors such as heavy metals or pH ranges outside normal ambient levels, etc.) and if they were based on good science. These decisions are, in part, subjective but follow the principles specified in the draft "Derivation of Water Quality Guidelines to Protect Aquatic Life in British Columbia" (Water Quality Branch, 1995).

The following discussions for freshwater aquatic life will focus on the studies shown in Table 2 with harmful effect levels < 1000 mg/L SO_4.

A discussion of the toxicity of sulphate to marine life was omitted from this section and a guideline for sea water was deemed unnecessary because of the high levels of sulphate typically present in sea water (see Section 3.3.2). In addition, there was a paucity of information on the toxic effects of sulphate to marine organisms.

5.1. EFFECTS ON ALGAE

5.1.1. FRESHWATER ALGAE

Based on experiments in an early study performed by Beauchamp (1954), McKee and Wolf (1963) reported that water containing < 0.5 mg/L sulphate will not support the growth of algae. The State of Kentucky also recognizes that sulphur is an essential plant nutient and that sulphate in excess of 0.5 mg/L is essential for algal growth (Kentucky Water Watch web site).

The lowest value of SO_4 in Table 2 that was reported toxic to phytoplankton (4 mg/L SO_4) by Jayaraj *et al.* (1992) was rejected from this assessment because the toxicity tests were designed to test for the ameliorative effects of calcium, magnesium and iron on copper, cadmium and nickel toxicity. The magnesium was added as $MgSO_4$.

The blue-green algae *Anabaena* was reported to undergo early sporulation when reared in sulphate-supplemented media at concentrations of 216 and 311 mg/L (as SO_4) according to Kanta and Sarma (1980).

The AQUIRE database reported effect levels of sodium sulphate on two algae species (*Microcystis aeruginosa* and *Selenastrum capricornutum*) from a study by Yamane *et al.* (1982). A review of the original report revealed that the compound tested was alkyl sulphate, not sodium sulphate. This data was rejected as a basis to derive a water quality guideline for sulphate because of potential interference of the alkyl group.

Bioassays performed for BC Ministry of Environment, Lands and Parks (MELP) at the Pacific Environmental Science Centre (PESC) using the freshwater algae *Selenastrum capricornutum* determined an IC50 for growth of 1868 mg/L SO_4 and a Lowest Observed Effect Concentration (LOEC) and No Lowest Observed Effect Concentration (NOEC) of

1111 and 370.4 mg/L, respectively. Deionized water was used as the diluent in the test which would not represent ambient conditions. (Unpublished BC MELP data, 1996).

BC Research Inc.(1998) performed a series of spiked sulphate laboratory bioassays to assess the impact of simulated mine plant effluent with elevated sulphate levels on aquatic organisms. Included in this suite of bioassays was a 72-h algal growth inhibition test using *Selanastrum capricornutum* exposed to the simulated effluent spiked with Na_2SO_4. A NOEC and LOEC of 1060 and 3650 mg/L SO_4, respectively, were reported. Also, an IC25 and IC50 for growth inhibition of 2210 and 3359 mg/L SO_4, respectively, were reported.

5.2. EFFECTS ON AQUATIC MACROPHYTES

Aquatic mosses appear to be the most sensitive freshwater organisms to sulphate that were identified in this review. The AQUIRE database transcribed data incorrectly from a study by Frahm (1975). AQUIRE reported mortality to four species of aquatic moss, *Fontinalis antipyretica, Fissendens crassipes, Leptodictum riparium,* and *Leskea polycarpa* at concentrations of 100 mg/L, 150 mg/L, >200 mg/L and >200 mg/L as K_2SO_4, respectively, after a one-week exposure. However, the original publication by Frahm (1975) reported these values measured as SO_4, not K_2SO_4, so conversions were unnecessary and the data reported accordingly. At least one species tested, *Fontinalis antipyretica,* is known to be widely distributed throughout BC, especially near the coast and in the lower pH waters.

To challenge the scientific reliability of the aquatic moss toxicity data reported by Frahm (1975), Beak International Incorporated, together with Michigan Technological University (1998) performed 14-day bioassays on the aquatic moss, *Fontinalis neomexicana*, exposed to sodium sulphate concentrations up to 500 mg/L (as SO_4) at water hardness of 160 mg/L (as $CaCO_3$). The responses measured were chlorophyll *a* and *b* content. Based on their observations, they concluded that sulphate concentrations up to 500 mg/L would not be harmful to aquatic life in hard water conditions such as those tested here. However, in-house plant specialists (P. Warrington and R. Nordin, personal communication) expressed some concern as to the merits of monitoring chlorophyll *a* and *b* content as a measure of moss health. The measurement of chlorophyll *a* and *b* content is really a surrogate measure of plant biomass and since aquatic mosses grow very slowly, such a measurement may be a poor indicator of the relatively short-term viability of moss populations exposed to sulphate. It was considered doubtful that chlorophyll *a* and *b* content in moss cuttings would change much under the test conditions. While chlorophyll content is fairly easy to measure, photosynthetic impairment, or a test designed to measure impairment of the naked free-swimming sperm would be a far better

measure of plant health, and of its ability to maintain a viable population in a stream system.

Stanley (1974) measured the effects of a number of compounds including Na_2SO_4 on the growth of Eurasian watermilfoil (*Myriophyllum spicatum L.*) over 32 days of exposure. Transposed effect values to the AQUIRE database appear to be incorrect. Corrected 32-d EC50's for root and stem growth ranged from 2785 to 7011 mg/L (as SO_4). The sodium may have been the active ingredient affecting turgor pressure. Lower concentrations of Na_2SO_4 stimulated growth.

5.3. EFFECTS ON INVERTEBRATES

5.3.1. FRESHWATER INVERTEBRATES

Acute Toxicity

Fisher *et al.* (1991) determined a 1-d LC50 of 112 mg/L for zebra mussels (*Dreissena polymorphia*) of 62 mg/L (as SO_4) exposed to K_2SO_4 as shown in Table 2. However, through a series of toxicity tests using potassium compounds, Fisher *et al.* (1991) concluded that the potassium (K^+ ion) was the toxic moiety of the compound to the zebra mussels, not the sulphate. This data was rejected as a basis to derive the sulphate water quality guideline because the sulphate did not cause the toxicity reported.

Effect levels of sodium and magnesium sulphate on amphipods (*Hyallela* sp.), mosquito larvae (*Culex* sp.), cladocerans (*Daphnia magna*), and pond snail eggs (*Lymnaea* sp.) cited from Dowden and Bennett (1965). These values appear to have been incorrectly transcribed from the original reference to the AQUIRE database. The results have been re-entered correctly to Table 2. The corrected 1- to 4-d LC50's for the amphipods exposed to Na_2SO_4 ranged from 595 to 1609 mg/L (as SO_4) The 1- and 2-d LC50 for the mosquito larvae exposed to Na_2SO_4 are 7727 and 9025 mg/L (as SO_4). The 1- to 4-d LC50 for *Daphnia magna* exposed to Na_2SO_4 and $MgSO_4$ ranged from 426 to 5668 mg/L (as SO_4). Corrected values for reduced hatching success of Lymnaea eggs exposed to Na_2SO_4 and $MgSO_4$ for 1- to 4-days ranged from 2402 to 8403 mg/L (as SO_4).

The AQUIRE database reported 1- and 2-d EC50's of 406 and 344 mg/L for *Daphnia magna* exposed to $MgSO_4$ from a study by Khangarot and Kay (1989). The concentrations in the original reference were reported as the Mg^{2+} ion concentration. Similarily, in a separate study by Khangarot (1991), the toxicity of Mg^{2+} ions were tested on tubificid worms (*Tubifex tubifex*) but the values transcribed to the AQUIRE database

were reported as the Mg^{2+} ion concentration. Hence, the data were not appropriate to serve as a basis for the derivation of sulphate water quality guidelines.

Fairchild (1955) reported that the threshold toxicity concentration of sodium sulphate toward Daphnia depended on the dissolved oxygen (DO) concentration. At a DO concentration of 6.6 mg/L, the toxicity threshold of Na_2SO_4 was 5514 mg/L; but at a DO concentration of 1.46 mg/L, the toxicity threshold of Na_2SO_4 dropped to 2752 mg/L.

BC MELP had The Pacific Environmental Science Centre (PESC) perform a series of acute toxicity bioassays using the freshwater invertebrates *Daphnia*, *Hyalella*, and Chironomids exposed to SO_4 under three different water hardnesses, 25, 100, and 250 mg/L (as $CaCO_3$). Generally, for most aquatic organisms tested including fish, toxicity decreased with increased water hardness. Chironomids were the only organisms that showed the opposite trend (Figure 3). Reported 48-h LC50s for *Daphnia* in soft water (hardness of 25 mg/L as $CaCO_3$), well water (hardness of 100 mg/L), and hard water (hardness of 250 mg/L), were 537, 6281, and 7442 mg/L SO_4, respectively. For *Hyalella*, reported 96-h LC50s in the soft, medium and hard water were 205, 3711, and 6787 mg/L, respectively. Chironomids appeared considerably less sensitive to SO_4 in soft water than the other invertebrates tested, where 96-h LC50s in the soft, medium, and hard water were 6667, 5868, and 4173 mg/L, respectively. (Unpublished PESC data, 1996). The hypersensitivity of *Hyalella* to sulphate demonstrated in the series of PESC bioassays conflicts with information cited by Beak (1997b), where *Hyalella azteca* is reported as one of a few freshwater organisms that thrives in saline prairie lakes containing 30 000 mg/L of dissolved salts, of which $MgSO_4$ is typically the dominant salt species. The reason for this discrepancy is not known but may be linked to the soft water used in the key PESC data or the acclimation of species over time.

As noted in Section 5.1.1, BC Research Inc.(1998) performed a series of spiked sulphate laboratory bioassays to assess the impact of elevated sulphate levels on aquatic organisms. Included in this suite of bioassays were a 48-h acute toxicity test using the cladoceran, *Daphnia magna*, and a 96-h survival test using the amphipod *Hyalella azteca*. Water hardness of the test solutions ranged from about 105 to 116 mg/L (as $CaCO_3$). For *Daphnia*, a NOEC and LOEC of 3650 and 7460 mg/L SO_4, respectively, and a 48-h LC50 of 5218 mg/L SO_4, was reported. For *Hyalella*, a NOEC and LOEC of 1060 and 3650 mg/L SO_4, respectively, were reported and, a 96-h LC50 of 1226 mg/L SO_4 was also determined.

Chronic Toxicity

To assess the chronic effects of elevated sulphate concentrations emanating from a Vancouver Island coal mine, Denisger (1997 draft) reported on chronic *Daphnia* bioassays performed at the Pacific Environmental Science Centre (PESC) using on-site water collected downstream from the mine. Control water for the test was laboratory source water from the Capilano River. Effects studied included reproductive success, survival time to first brood, and growth or mobility inhibition. Four of six site waters tested showed no environmental effects for *Daphnia* after chronic exposure however, reproduction and survival effects at one of the sites could not be explained by differences in water quality, and toxicity at the other site was thought possibly to be due to hydrogen sulphide detected in the test water. The highest dissolved sulphate concentration used in the *Daphnia* laboratory bioassays was 420 mg/L from settling pond and coal wash plant drainage. No significant difference in effects was noted for *Daphnia* between this test water and the control.

BC MELP requisitioned PESC to conduct 21-day chronic *Daphnia* bioassays to assess the toxicity of SO_4 in water of hardness 100 mg/L and 250 mg/L (as $CaCO_3$). No chronic *Daphnia* tests were performed in the soft water (25 mg/L as $CaCO_3$) because Daphnia typically do not survive well in soft water. A LOEC, NOEC, and an IC25 (25% inhibition of reproduction) of 1200, 625, and 833 mg/L SO_4, respectively were reported for medium water hardness. In hard water, a LOEC, NOEC, and an IC25 of 1375, 795, and 1476 mg/L SO_4 were reported (Unpublished PESC data, 1996).

As noted in Section 5.1.1, BC Research Inc.(1998) performed a series of spiked sulphate laboratory bioassays to assess elevated sulphate levels. Included in this suite of bioassays was a 7-day survival test using the cladoceran , *Ceriodaphnia*. A NOEC and LOEC of 1060 and 3650 mg/L SO_4, respectively, were reported. A 7-day IC25 and IC50 for reproduction of 1267 and 2061 mg/L SO_4, respectively, were reported, as well as a 7-day LC50 of 1355 mg/L SO_4.

5.4. EFFECTS ON FISH

5.4.1. FRESHWATER FISH

Acute Toxicity

The lowest toxic values to freshwater fish reported in the AQUIRE aquatic toxicological database were 15 and 22 mg/L (converted to SO_4) after five days of exposure. However, the original published study (Horn *et al.* (1949) from which these data were derived reported only one minimum lethal concentration of 100 mg/L Na_2SO_4 (equivalent to 67.6 mg/L SO_4). This value was based on a screening test using one to five emerald shiners (Notropis atherinoides). The AQUIRE reference relied upon author communication for

the data reported. In view of the publication date of this study (1949), reliable confirmation of these reported values is unlikely. In addition, according to the original reference, only one fish may have been used in the test and no control tests were reported. In view of these factors, the values reported in this study were rejected as a basis to derive a water quality guideline for sulphate.

The AQUIRE database reported several LC50 values ranging from 55 to 744 mg/L for Na_2SO_4 (converted to SO_4 by this author) on striped bass (*Morone saxatilus*) by Hughes (1973) that were cited from a secondary reference. These secondarily reported data in the AQUIRE database do not agree with the original published data and therefore were rejected by this author. The original data from Hughes (1973) has been added to Table 2 directly below the rejected data. These corrected 1 to 4-day LC50's ranged from 2000 to 250 mg/L SO_4 , respectively for striped bass larvae. The 4-day LC50 of 250 mg/L SO_4 for *Morone saxatilus* larvae was the lowest (most toxic), reliable toxic concentration reported in the literature reviewed for fish. The lowest LC0 (no mortality) for this species was 100 mg/L after four days of exposure. One to 4-day LC50's reported for striped bass fingerlings were all 3500 mg/L and the LC0 for all exposure durations (1- to 4-day) was 2500 mg/L. While this particular species of bass is not resident in British Columbia, this species serves as an indicator for bass (largemouth and smallmouth bass) and perch (yellow perch) species that are indigenous to BC but for which no toxicological data exists.

The AQUIRE database reported several effect levels of sodium and magnesium sulphate on bluegills (*Lepomis macrochirus*) and gobbies (*M. latipinna*) cited from Dowden and Bennett (1965). These values appear to have been incorrectly transcribed from the original reference to the AQUIRE database and have now been re-entered correctly to Table 2. The corrected 1-d LC50's for exposure of *Lepomis macrochirus* to Na_2SO_4 and $MgSO_4$ are 11 831 and 15 162 mg/L (as SO_4). The corrected 1- and 2-d LC50's for exposure of *M. latipinna* to Na_2SO_4 are 11 831 and 13 548 mg/L (as SO_4).

Wallen *et al.* (1957) tested the toxicities of Na_2SO_4, $MgSO_4$ and $CaSO_4$ separately to the mosquito fish (*Gambusia affinis*) in the presence of high turbidity (measured with a Jackson turbidimeter but results reported as ppm?) which ranged from between 3000 mg/L at the onset of the tests to <25 mg/L at the end to simulate turbid water conditions in Oklahoma. The results tabulated in the AQUIRE database appear to have been incorrectly transcribed from the original reference. The corrected data was entered into Table 2. One to 6-d LC50 concentrations for Na_2SO_4, $MgSO_4$ and $CaSO_4$ ranged from 6761 to 44 688 mg/L (as SO_4). The highly turbid diluent water used in the tests disqualify the results as a basis for a water quality guideline for BC waters.

Tsuji *et al.* (1985) reported 1- and 2-d LC50's of >1000 mg/L for killifish (*Oryzias latipes*) exposed to $MgSO_4$ at three temperatures (10, 20 and 30°C). These concentrations were reported as the metal concentration (Mg), not $MgSO_4$ as reported in the AQUIRE database. Hence, these data are not suitable as a basis to derive a water quality guideline for sulphate.

Boge *et al.* (1982a,b) studied the effects of sulphate ions on enzymatic activities in the gut and gill of the European eel (*Anguilla anguilla*) under constant temperature conditions and when exposed to heat shock. Changes in enzyme activity were noted under both temperature regimes when exposed to 176 mg/L SO_4, when applied as K_2SO_4 and $CaSO_4$. This concentration includes the sulphate concentration of the diluent which already contained 76 mg/L SO_4. While biochemical changes were noted, these may be an adaptive response and may not result in detrimental physiological effects. The European eel is not indigenous to British Columbia.

Boge *et al.* (1982c,d) performed identical studies on enzymatic activity using rainbow trout (*Oncorhynchus mykiss*) in place of eels. No changes were noted when exposed to the same sulphate concentration (176 mg/L as SO_4) and under the same temperature regimes as the eels.

BC MELP contracted PESC to perform a series of acute toxicity bioassays using rainbow trout (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*) exposed to SO_4 under different water hardness conditions. Generally, for most aquatic organisms tested including fish, toxicity decreased with increased water hardness. The 96-h LC50s for rainbow trout in soft water (hardness of 25 mg/L as $CaCO_3$), well water (hardness of 100 mg/L), and hard water (hardness of 250 mg/L), were 5000, 9750, and 9900 mg/L SO_4, respectively. For coho salmon, 96-h LC50s for the soft, medium, and hard water were 5742, 9550, and 9875 mg/L, respectively (Unpublished BC MELP data, 1996).

Chronic Toxicity

To assess the chronic effects of elevated sulphate concentrations emanating from a coal mine, Denisger (1997 draft) performed *in-situ* chronic coho salmon (*Oncorhynchus kisutch*) egg bioassays in the Quinsam River watershed near Nanaimo, BC. An intensive water quality monitoring program was conducted in conjunction with the bioassays. Four test sites and one control site were chosen for the study. The site with the highest dissolved sulphate concentration (drainage from the settling pond and coal wash plant) ranged from 281 to 1111 mg/L. Coho egg mortality of 20% was reported at this site. The author suggested that the predominant factor affecting

toxicity of the coho eggs at this site may have been the elevated sulphate levels. A sample of this same site water was used to test *Daphnia* in the laboratory (sulphate concentration of 420 mg/L) but showed no significant toxicity over the control water (see Section 6.3.1).

Beak International Incorp. (1997b) has reported field observations from sulphate-enriched waters near three separate minesites in Ontario, Quebec, and New Brunswick. At the Quebec site (Beak, 1996a), salmon survival was reportedly unimpaired at sulphate concentrations of 45 to 160 mg/L in spring and from 180 to 300 mg/L in fall. Similarly, at the New Brunswick minesite (Beak, 1997a), benthic and fish communities were reportedly unimpaired at sulphate concentrations which ranged from 170 to 250 mg/L. Any harmful effects noted in exposed aquatic organisms during these field observations were attributed to substances other than sulphate, such as metals or ammonia. Assessment of the relevance of sulphate toxicity from such field observations is often difficult due to the uncontrolled influence of confounding factors.

BC MELP had the Pacific Environmental Science Centre (PESC) perform 7-day early life stage (e-test) rainbow trout bioassays exposed to SO_4 under different water hardness conditions. Reported 7-day EC50's for the young rainbow trout in soft water (hardness of 25 mg/L as $CaCO_3$), well water (hardness of 100 mg/L), and hard water (hardness = 250 mg/L), were 1105, 1025, and 3116 mg/L SO_4, respectively (Unpublished BC MELP data, 1996).

As noted in Section 5.1.1, BC Research Inc.(1998) performed a series of spiked sulphate laboratory bioassays to assess elevated sulphate levels on aquatic organisms. Included in this suite of bioassays were a 7-day salmonid embryo viability test (e-test) using the rainbow trout, *Onchorhynchus mykiss*, and a 7-day survival and growth test using the fathead minnow *Pimephales promelas*. For rainbow trout embryo viability, a NOEC and LOEC of 1060 and 3500 mg/L SO_4, respectively, were reported. A 7-day EC25 and EC50 for viability of 1280 and 1477 mg/L SO_4, respectively, were also reported for the trout embryos. For the fathead minnow test, a NOEC and LOEC for survival of 510 and 1060 mg/L SO_4, respectively, were reported, and for growth, a NOEC and LOEC of 1060 and 3650 mg/L SO_4, respectively, were reported. Also, an IC25 and IC50 for growth of 2255 and 3450 mg/L SO_4, respectively, were determined, as well as a 7-day LC50 of 1355 mg/L SO_4.

In an earlier publication McKee and Wolf (1963) reported that of good game fish waters in the U.S., five percent of these waters contain <11 mg/L sulphates, 50 % <32 mg/L, and 95 % < 90 mg/L.

5.5. GUIDELINES FROM THE LITERATURE

A provisional water quality objective of 100 mg/L maximum for sulphate was set for the Yakoun River and its tributaries to protect aquatic life (Nijman, 1993). This objective was based on toxicity studies using eels (*Anguilla anguilla*) and fish (striped bass *Morone saxatilus*) that are not resident in BC waters (see Section 6.5.1).

A Provisional water quality objective for sulphate of 50 mg/L average concentration (five samples in 30 days) was set for Cahill Creek, Nickel Plate Mine Creek, and Red Top Gulch Creek in the Okanagan area of BC (Swain, 1987). The rationale behind this objective is that, according to Beatty, (personal communication), above an average concentration of 71 mg/L sulphate (range of 27.7 to 189 mg/L) large sulphur bacteria growths can cover creek beds and result in significant changes to the macroinvertebrate community. However, at another location in the Okanagan area, despite sulphate concentrations which have averaged between 150 to 450 mg/L for about the past decade, no dense growths of sulphate bacteria have been observed (J. E. Bryan, personal communication).

5.6. RECOMMENDED GUIDELINE

5.6.1. FRESHWATER AQUATIC LIFE

To protect freshwater organisms in British Columbia, a water quality guideline of 100 mg/L for dissolved sulphate, measured as SO_4, is recommended. This guideline is a maximum concentration that should not be exceeded at any time.
Since there is conflicting evidence over the sensitivity of aquatic mosses to sulphate it is recommended that for impacted waterbodies with concentrations of dissolved sulphate that exceed 50 mg/L, the health of aquatic moss populations should be checked on an occasional basis.

5.6.2. RATIONALE

The guideline is based primarily on three studies which investigated the effects of sulphate on freshwater organisms. These are as follows:

i. Hughes (1973) reported 1-, 2-, 3-, and 4-d LC50's of 2000, 1000, 500, and 250 mg/L for SO_4, and LC0's (no effect) of 500, 100, 100, and 100 mg/L, respectively, for striped bass (*Morone saxitilus*) larvae.

ii. Unpublished data from a series of toxicity tests performed by The Pacific Environmental Science Centre (PESC) for BC MELP in 1996 showed that the amphipod, *Hyalella*, was sensitive to sulphate in soft water, but not in medium (100 mg/L as $CaCO_3$) to hard water (250 mg/L as $CaCO_3$). PESC reported 96-h LC50s for *Hyalella* in soft, medium and hard water of 205, 3711, and 6787 mg/L SO_4,

respectively. A water quality guideline of 100 mg/L provides protection with a 2:1 safety factor in soft water, and a significantly greater safety factor in harder water more typical throughout BC.

iii. Frahm (1975) demonstated that a concentation of 100 mg/L SO_4 was toxic to the aquatic moss, *Fontinalis antipyretica*, a species which is known to be widely distributed throughout BC. Toxicity of SO_4 to four other species of aquatic moss ranged from 100 to >250 mg/L. There are more recent data (Beak International Incorporated and Michigan Technological University, 1998) that conflicts with these earlier (Frahm, 1975) data but the chosen endpoint of the newer data is in question.

iv. There is some evidence that elevated sulphate levels (average of 71 mg/L sulphate; range of 27.7 to 189 mg/L) can stimulate large sulphur bacteria growths which can cover creek beds and result in significant changes to the macroinvertebrate community. Anecdotal evidence is not used to derive water quality guidelines due to the absence of scientific defensibility of such information. But such information is worth noting to provide the impetus to stimulate the necessary future research into such observations.

5.6.3. APPLICATION OF GUIDELINE

There is some evidence that increased water hardness ameliorates sulphate toxicity which may allow for a site-specific sulphate objective that is less stringent than the guideline recommended here. " To adjust the guideline recommended here to take local conditions into consideration, the BC Environment publication, *"Methods for Deriving Site-Specific Water Quality Objectives in British Columbia and Yukon"* should be followed.

6. OTHER WATER-USE CATEGORIES

Guidelines for other water-use categories were considered unnecessary at this time.

7. RESEARCH AND DEVELOPMENT NEEDS

- Perform toxicity tests using a sensitive endpoint, such as a change in photosynthetic activity, on indigenous BC aquatic moss species including *Fontinalis antipyretica* to check their high sensitivity to SO_4 as reported in the study by Frahm (1975).
- Scientific investigation of anecdotal evidence that elevated sulphate levels can stimulate large sulphur bacteria growths which can cover creek beds and result in significant changes to the macroinvertebrate community.

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TABLES

Table 1: Summary of Ambient Dissolved Sulphate Concentrations in BC Freshwaters

Site/Location	No. of Values	Maximum mg/L	Minimum mg/L	Mean mg/L	Standard Error Standard Dev	Reference
Lizard Lake, Vancouver Island	105	1.57	1.06	1.28	SE 0.01	Phippen et al., 1996
Marion Lake, Lower Mainland	80	2.3	0.92	1.65	SE 0.03	Phippen et al., 1996
Maxwell Lake, Saltspring Island	15	4.3	3	3.43	SE 0.084	Phippen et al., 1996
Old Wolf Lake, Vancouver Island	19	5.1	1	1.9	SE 0.33	Phippen et al., 1996
Spectacle Lake, Vancouver Island	15	4.3	2	2.89	SE 0.207	Phippen et al., 1996
Stocking Lake, Vancouver Island	6	2	1.7	1.85	SE 0.043	Phippen et al., 1996
Shawnigan Lake, Vancouver Island	8	5	2.3	4.3	SD 1.20	BC MELP and EC, 1996a
Salmon River, Near Hyder Alaska	300*	50*	2*	20*	NR	BC MELP and EC, 1996b
Quinsam River, Vancouver Island	200*	14*	2*	4*	NR	BC MELP and EC, 1996c
Quamichan Lake, Vancouver Island	6	19.1	14.3	17.25	SD 2.24	BC MELP and EC, 1996d
Prospect Lake, Vancouver Island	5	<0.5	<0.5	<0.5	0	BC MELP and EC, 1996e
Okanagan River, Oliver	300*	40*	15*	27*	NR	BC MELP and EC, 1996f
Langford Lake, Vancouver Island	4	24.9	7.9	16.18	SD 8.523	BC MELP and EC, 1996g
Kootenay River, Picture Valley	260*	60*	10*	37*	NR	BC MELP and EC, 1996h
Kootenay River, Creston	300*	22*	3*	15*	NR	BC MELP and EC, 1996i
Kettle River, Carson	300*	20*	3*	10*	NR	BC MELP and EC, 1996j
Kettle River, Midway	300*	17*	2*	7.5*	NR	BC MELP and EC, 1996k
Kettle River, Gilpin	300*	17*	1.5*	8*	NR	BC MELP and EC, 1996m
Glen Lake, Vancouver Island	24	0.5	0.5	0.5	SD 0	BC MELP and EC, 1996n
Fraser River, Red Pass	20*	17*	2.5*	7.5*	NR	BC MELP and EC, 1996p
Fraser River, Marguerite	200*	15*	4*	10*	NR	BC MELP and EC, 1996q
Fraser River, Hansard	225*	18*	3*	12*	NR	BC MELP and EC, 1996r
Elk River, Phillips Bridge Hwy 93	225*	40*	5*	25*	NR	BC MELP and EC, 1997a
Elk/Beaver Lakes Vancouver Island	4	12.9	7.6	10.3	SD 2.89	BC MELP and EC, 1996s

Table 1: Summary of Ambient Dissolved Sulphate Concentrations in BC Freshwaters (Cont'd)

Site/Location	No. of Values	Maximum mg/L	Minimum mg/L	Mean mg/L	Standard Error Standard Dev	Reference
Boundary Creek, Midway	90*	50*	5*	25*	NR	BC MELP and EC, 1996t
Bear River, Stewart	180*	45*	7*	27*	NR	BC MELP and EC, 1996u
Peace River, Above Alces River	200*	22*	6*	13*	NR	BC MELP and EC, 1996v
Alsek River, Above Bates River	16*	26*	15*	20*	NR	BC MELP and EC, 1996w
Unuk River, Near U.S. Border	16*	32*	9*	24*	NR	BC MELP and EC, 1996x
Iskut River, Below Johnson River	120*	35*	9*	20*	NR	BC MELP and EC, 1996y
Stikine River, Above Choquette River	80*	19*	6*	12*	NR	BC MELP and EC, 1996z
Liard River, At lower crossing	70*	23.5*	7.5*	15*	NR	BC MELP and EC, 1996aa
Liard River, At upper crossing	200*	17.5*	2.5*	10*	NR	BC MELP and EC, 1996ab
Liard River, At Fort Liard	100*	48*	15*	30*	NR	BC MELP and EC, 1996ac

* Values are estimated visually from charted data

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Anabaena sp Blue-green algae	20	BIO	320000	216	Na2SO4	rejected: does not agree with original study	5052
Anabaena sp Blue-green algae	20	BIO	460000	311	Na2SO4	rejected: does not agree with original study	5052
Anabaena sp Blue-green algae	20	BIO	.1MSO4	**9600**	Na2SO4	corrected from original reference	5052
Selenastrum capricornutum Green algae	3	IC50 (growth)		**1868**	Na2SO4	water hardness = 0 mg/L (deionized water)	BC MELP
Selenastrum capricornutum Green algae	3	LOEC		**1111**	Na2SO4	water hardness = 0 mg/L (deionized water)	BC MELP
Selenastrum capricornutum Green algae	3	NOEC		**370**	Na2SO4	water hardness = 0 mg/L (deionized water)	BC MELP
Selenastrum capricornutum Green algae	3	NOEL		**1060**	Na2SO4	water hardness: approx 100 mg/L	BC Research
Selenastrum capricornutum Green algae	3	LOEL		**3650**	Na2SO4	water hardness: approx 100 mg/L	BC Research
Selenastrum capricornutum Green algae	3	IC25 (growth)		**2210**	Na2SO4	water hardness: approx 100 mg/L	BC Research
Selenastrum capricornutum Green algae	3	IC50 (growth)		**3359**	Na2SO4	water hardness: approx 100 mg/L	BC Research
Culex sp Mosquito	1	LC50 MOR	3704000	2504	Na2SO4	rejected: does not agree with original study	915
Culex sp Mosquito	1	LC50 MOR	2572000	1739	Na2SO4	rejected: does not agree with original study	915
Culex sp Mosquito	2	LC50 MOR	4325000	2924	Na2SO4	rejected: does not agree with original study	915
Culex sp Mosquito	2	LC50 MOR	3004000	2031	Na2SO4	rejected: does not agree with original study	915
Amphipoda species not given	1	LC50 MOR	2380000	**1609**	Na2SO4	corrected from original reference	915
Amphipoda species not given	2	LC50 MOR	1110000	**750**	Na2SO4	corrected from original reference	915
Amphipoda species not given	3	LC50 MOR	880000	**595**	Na2SO4	corrected from original reference	915
Amphipoda species not given	4	LC50 MOR	880000	**595**	Na2SO4	corrected from original reference	915
Culex sp	1	LC50 MOR	11430000	**7727**	Na2SO4	corrected from original reference	915

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Mosquito							
Culex sp	2	LC50 MOR	13350000	**9025**	Na2SO4	corrected from original reference	915
Mosquito							
Daphnia magna	1	LC50 MOR	8384000	**5668**	Na2SO4	corrected from original reference	915
Water flea							
Daphnia magna	2	LC50 MOR	2564000	**1733**	Na2SO4	corrected from original reference	915
Water flea							
Daphnia magna	3	LC50* MOR	725000	**490**	Na2SO4*	corrected from original reference	915
Water flea							
Daphnia magna	4	LC50 MOR	630000	**426**	Na2SO4	corrected from original reference	915
Water flea							
Daphnia magna (adult)	4	LC50 MOR	4547000	**3074**	Na2SO4	corrected from original reference	915
Water flea							
Daphnia magna (young)	1	LC50 MOR	6800000	**4597**	Na2SO4	corrected from original reference	915
Water flea							
Daphnia magna (young)	2	LC50 MOR	6100000	**4124**	Na2SO4	corrected from original reference	915
Water flea							
Lepomis macrochirus	1	LC50 MOR	17500000	**11831**	Na2SO4	corrected from original reference	915
Bluegill							
Lymnaea sp	1	EC50 HAT	5401000	**3651**	Na2SO4	corrected from original reference	915
Pond snail							
Lymnaea sp	2	EC50 HAT	5400000	**3651**	Na2SO4	corrected from original reference	915
Pond snail							
Lymnaea sp	3	EC50 HAT	5400000	**3651**	Na2SO4	corrected from original reference	915
Pond snail							
Lymnaea sp	4	EC50 HAT	3553000	**2402**	Na2SO4	corrected from original reference	915
Pond snail							
M. latipinna	1	LC50 MOR	20040000	**13548**	Na2SO4	corrected from original reference	915
Molly							
M. latipinna	2	LC50 MOR	15996000	**10814**	Na2SO4	corrected from original reference	915
Molly							
Cyprinidae	1	MOR	4500000	**3042**	Na2SO4	original reference not checked	2540
Minnow , carp family							
Daphnia magna	0.01	LOC	2302000	**1556**	Na2SO4	original reference not checked	2171
Water flea							
Daphnia magna	0.01	LOC	1601000	**1082**	Na2SO4	original reference not checked	2171
Water flea							

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name / Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Daphnia magna	4.2	EC50 IMM	4547000	**3074**	Na2SO4	original reference not checked	2462
Water flea							
Daphnia magna	2	LC50 MOR	4.25605 mmol/	**9124**	Na2SO4	original reference not checked	13712
Water flea							
Daphnia magna	1	LC50 MOR	2200000	1487	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	1	LC50 MOR	2716000	1836	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	1	LC50 MOR	8384000	**5668**	Na2SO4	original reference not checked	2465
Water flea							
Daphnia magna	1	LC50 MOR	1889000	1277	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	1	LC50 MOR	1530000	1034	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50 MOR	1980000	1339	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50 MOR	830000	561	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50 MOR	578000	391	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50 MOR	1373000	928	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50* MOR	2564000	**1733**	Na2SO4	original reference not checked	2465
Water flea							
Daphnia magna	3	LC50 MOR	234000	158	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	3	LC50 MOR	163000	110	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	204000	138	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	1470000	994	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	142000	96	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	1024000	692	Na2SO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LETC IMM	5960000	**4029**	Na2SO4	original reference not checked	2130

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Water flea							
Daphnia magna	2	LC50		537	Na2SO4	water hardness = 25 mg/L	BC MELP
Water flea							
Daphnia magna	2	LC50		6281	Na2SO4	water hardness = 100 mg/L	BC MELP
Water flea							
Daphnia magna	2	LC50		7442	Na2SO4	water hardness = 250 mg/L	BC MELP
Water flea							
Daphnia magna	21	LOEC		1200	Na2SO4	water hardness = 100 mg/L	BC MELP
Water flea							
Daphnia magna	21	LOEC		1375	Na2SO4	water hardness = 250 mg/L	BC MELP
Water flea							
Daphnia magna	21	IC25 (reproduction)		833	Na2SO4	water hardness = 100 mg/L	BC MELP
Water flea							
Daphnia magna	21	IC25 (reproduction)		1476	Na2SO4	water hardness = 250 mg/L	BC MELP
Water flea							
Hyallela sp	4	LC50		205	Na2SO4	water hardness = 25 mg/L	BC MELP
Amphipoda							
Hyallela sp	4	LC50		3711	Na2SO4	water hardness = 100 mg/L	BC MELP
Amphipoda							
Hyallela sp	4	LC50		6787	Na2SO4	water hardness = 250 mg/L	BC MELP
Amphipoda							
Chironomus tetans	4	LC50		6667	Na2SO4	water hardness = 25 mg/L	BC MELP
Chironomid							
Chironomus tetans	4	LC50		5868	Na2SO4	water hardness = 100 mg/L	BC MELP
Chironomid							
Chironomus tetans	4	LC50		4173	Na2SO4	water hardness = 250 mg/L	BC MELP
Chironomid							
Daphnia Magna	2	NOEC		3650	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Water flea							
Daphnia Magna	2	LOEC		7460	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Water flea							
Daphnia Magna	2	LC50		5218	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Water flea							
Hyallela azteca	4	NOEC-Survival		1060	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Amphipoda							
Hyallela azteca	4	LOEC-Survival		3650	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Amphipoda							

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Hyallela azteca	4	LC50		1226	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Amphipoda							
Ceriodaphnia	7	NOEC-Survival/reprod.		1060	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Cladoceran							
Ceriodaphnia	7	LOEC-Survival/reprod.		3650	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Cladoceran							
Ceriodaphnia	7	IC25-Reproduction		1267	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Cladoceran							
Ceriodaphnia	7	IC50-Reproduction		2061	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Cladoceran							
Ceriodaphnia	7	LC50-Survival		1967	Na2SO4	water hardness: approx 100 mg/L	Bc Research
Cladoceran							
Gambusia affinis	4	MOR	720000	487	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	4	MOR	1000000	676	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	1	LC50 MOR	5400000	3651	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	1	LC50 MOR	7800000	5273	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	2	LC50 MOR	3940000	2664	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	2	LC50 MOR	5670000	3833	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	4	LC50 MOR	3710000	2508	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	4	LC50* MOR	5350000	3617	Na2SO4*	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	6	LC50 MOR	2200000	1487	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	6	LC50 MOR	3200000	2163	Na2SO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	1	LC50 MOR	24000000	16225	Na2SO4	reject: turbid diluent; corrected from orig. ref.	508
Mosquitofish							
Gambusia affinis	2	LC50 MOR	17500000	11831	Na2SO4	reject: turbid diluent; corrected from orig. ref.	508
Mosquitofish							
Gambusia affinis	4	LC50 MOR	16500000	11155	Na2SO4	reject: turbid diluent; corrected from orig. ref.	508

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Mosquitofish							
Gambusia affinis	6	LC50 MOR	10000000	6761	Na2SO4	reject: turbid diluent; corrected from orig. ref.	508
Mosquitofish							
Lepomis macrochirus	1	LC50 MOR	5670000	3833	Na2SO4	rejected: does not agree with original study	915
Bluegill							
Lepomis macrochirus	1	LC50 MOR	3940000	2664	Na2SO4	rejected: does not agree with original study	915
Bluegill							
Lepomis macrochirus	4	LC50 MOR	4380000	2961	Na2SO4	original reference not checked	8037
Bluegill							
Lepomis macrochirus	4	LC50 MOR	3040000	2055	Na2SO4	original reference not checked	8037
Bluegill							
Lymnaea sp	1	EC50 HAT	1750000	1183	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	1	EC50 HAT	1215000	821	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	2	EC50* HAT	1750000	1183	Na2SO4*	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	2	EC50 HAT	1215000	821	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	3	EC50 HAT	1750000	1183	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	3	EC50 HAT	1215000	821	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	4	EC50 HAT	1151000	778	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Lymnaea sp	4	EC50 HAT	799000	540	Na2SO4	rejected: does not agree with original study	915
Pond snail							
Microcystis aeruginosa		NR EC50 PGR >	800000	541	Na2SO4	rejected: organic sulphates tested	9715
Blue-green algae							
Morone saxatilis	1	LC50 MOR	650000	439	Na2SO4	rejected: quoted from secondary ref by	2012
Striped bass						AQUIRE which does not agree with original	
Morone saxatilis	1	LC50 MOR	1100000	744	Na2SO4	"	2012
Striped bass							
Morone saxatilis	1	LC50 MOR	450000	304	Na2SO4	"	2012
Striped bass							
Morone saxatilis	1	LC50 MOR	790000	534	Na2SO4	"	2012
Striped bass							

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Morone saxatilis Striped bass	2	LC50 MOR	320000	216	Na2SO4	*	2012
Morone saxatilis Striped bass	2	LC50 MOR	1100000	744	Na2SO4	*	2012
Morone saxatilis Striped bass	2	LC50 MOR	220000	149	Na2SO4*	*	2012
Morone saxatilis Striped bass	2	LC50 MOR	790000	534	Na2SO4	*	2012
Morone saxatilis Striped bass	3	LC50 MOR	160000	108	Na2SO4	*	2012
Morone saxatilis Striped bass	3	LC50 MOR	1100000	744	Na2SO4	*	2012
Morone saxatilis Striped bass	3	LC50 MOR	110000	74	Na2SO4	*	2012
Morone saxatilis Striped bass	3	LC50 MOR	790000	534	Na2SO4	*	2012
Morone saxatilis Striped bass	4	LC50 MOR	81000	55	Na2SO4	*	2012
Morone saxatilis Striped bass	4	LC50 MOR	1100000	744	Na2SO4	*	2012
Morone saxatilis Striped bass	4	LC50 MOR	56000	38	Na2SO4	*	2012
Morone saxatilis Striped bass	4	LC50 MOR	790000	534	Na2SO4	*	2012
Morone saxatilis Striped bass larvae	1	LC50 MOR		**2000**	Na2SO4	cited from original: data reported as SO4	2012
Morone saxatilis Striped bass larvae	2	LC50 MOR		**1000**	Na2SO4	cited from original: data reported as SO4	2012
Morone saxatilis Striped bass larvae	3	LC50 MOR		**500**	Na2SO4	cited from original: data reported as SO4	2012
Morone saxatilis Striped bass larvae	4	LC50 MOR		**250**	Na2SO4*	cited from original: data reported as SO4	2012
Morone saxatilis Striped bass larvae	1	LC50 MOR		**3500**	Na2SO4	cited from original: data reported as SO4	2012
Morone saxatilis Striped bass larvae	2	LC50 MOR		**3500**	Na2SO4	cited from original: data reported as SO4	2012
Morone saxatilis	3	LC50 MOR		**3500**	Na2SO4	cited from original: data reported as SO4	2012

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name	Duration	Endpoint/Effect	Conc XSO4	Conc SO4	Test	Comments	Ref No.
Species Common Name	(days)		(ug/L)	(mg/L)	Chemical		see last page
Striped bass larvae							
Morone saxatilis	4	LC50 MOR		**3500**	Na2SO4	cited from original: data reported as SO4	2012
Striped bass larvae							
Myriophyllum spicatum	32	EC50 BMS	2305000	1558	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 BMS	2113000	1429	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 BMS	3313000	2240	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 BMS	3037000	2053	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	2337000	1580	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	928000	627	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	3360000	2272	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	1335000	903	Na2SO4	rejected: does not agree with original study	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	10228000	**6915**	Na2SO4*	corrected from original reference	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	9376000	**6339**	Na2SO4	corrected from original reference	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	10370000	**7011**	Na2SO4	corrected from original reference	2262
Eurasian watermilfoil							
Myriophyllum spicatum	32	EC50 GRO	4120000	**2785**	Na2SO4	corrected from original reference	2262
Eurasian watermilfoil							
Aquatic moss	14	Chlor *a* & *b* content		**500**	Na2SO4	no observed effect @ highest level tested	Beak & MTU
Fontinalis neomexicana							
Nitzschia fonticola		NR EC50 PGR >	800000	**541**	Na2SO4	rejected: organic sulphates tested	9715
Diatom							
Nitzschia linearis	5	LC50 MOR	1900000	**1285**	Na2SO4	original reference not checked	949
Diatom							
Notropis atherinoides	5	NR-LETH MOR	32000	22	Na2SO4	rejected: screening test only using 1 to 5 fish	663
Emerald shiner						and no controls	
Notropis atherinoides	5	NR-LETH MOR	22000	15	Na2SO4	"	663
Emerald shiner							

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name / Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No.
Notropis spilopterus	5	NR-LETH MOR	32000	22	Na2SO4	*	see last page
Spotfin shiner							663
Notropis spilopterus	5	NR-LETH MOR	22000	15	Na2SO4	*	
Spotfin shiner							663
Oncorhynchus mykiss	4	LC50 MOR		5000	Na2SO4	water hardness = 25 mg/L	BC MELP
Rainbow trout							
Oncorhynchus mykiss	4	LC50 MOR		9750	Na2SO4	water hardness = 100 mg/L	BC MELP
Rainbow trout							
Oncorhynchus mykiss	4	LC50 MOR		9900	Na2SO4	water hardness = 250 mg/L	BC MELP
Rainbow trout							
Oncorhynchus kisutch	4	LC50 MOR		5742	Na2SO4	water hardness = 25 mg/L	BC MELP
Coho salmon							
Oncorhynchus kisutch	4	LC50 MOR		9550	Na2SO4	water hardness = 100 mg/L	BC MELP
Coho salmon							
Oncorhynchus kisutch	4	LC50 MOR		9875	Na2SO4	water hardness = 250 mg/L	BC MELP
Coho salmon							
Oncorhynchus mykiss	7	Early life stage (e-test)		1105	Na2SO4	water hardness = 25 mg/L	BC MELP
Rainbow trout							
Oncorhynchus mykiss	7	Early life stage (e-test)		1925	Na2SO4	water hardness = 100 mg/L	BC MELP
Rainbow trout							
Oncorhynchus mykiss	7	Early life stage (e-test)		3116	Na2SO4	water hardness = 250 mg/L	BC MELP
Rainbow trout							
Oncorhynchus mykiss	7	NOEC (e-test)		1060	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Rainbow trout							
Oncorhynchus mykiss	7	LOEC (e-test)		3500	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Rainbow trout							
Oncorhynchus mykiss	7	EC25 (viability)		1280	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Rainbow trout							
Oncorhynchus mykiss	7	EC50 (viability)		1477	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Rainbow trout							
Pimephales promelas	7	NOEC (survival)		510	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Pimephales promelas	7	NOEC (growth)		1060	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Pimephales promelas	7	LOEC (survival)		1060	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Pimephales promelas	7	LOEC (growth)		3650	Na2SO4	water hardness: approx. 100 mg/L	BC Research

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name	Duration	Endpoint/Effect	Conc XSO4	Conc SO4	Test	Comments	Ref No.
Species Common Name	(days)		(ug/L)	(mg/L)	Chemical		see last page
Fathead minnow							
Pimephales promelas	7	IC25 (growth)		**2255**	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Pimephales promelas	7	IC50 (growth)		**3450**	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Pimephales promelas	7	LC50 (survival)		**1355**	Na2SO4	water hardness: approx. 100 mg/L	BC Research
Fathead minnow							
Polycelis nigra	2	LT50 MOR	0.048 M	**6816**	Na2SO4	original reference not checked	10013
Planarian							
Selenastrum capricornutum		NR EC50 PGR >	800000	541	Na2SO4	rejected: organic sulphates tested	9715
Green algae							
Chlorella vulgaris	91.3	LOEC PGR	1230000	**982**	MgSO4	original reference not checked	2849
Green algae	122						
Chlorella vulgaris	91.3	NOEC PGR	980000	**782**	MgSO4	original reference not checked	2849
Green algae	122						
Daphnia magna	1	EC50 IMM	405980	324	MgSO4	rejected: reported in orig. ref as Mg ion conc	6631
Water flea							
Daphnia magna	2	EC50 IMM	343560	274	MgSO4	rejected: reported in orig. ref as Mg ion conc	6631
Water flea							
Daphnia magna	1	LC50 MOR	193000	154	MgSO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	2	LC50 MOR	186000	148	MgSO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	3	LC50* MOR	172000	137	MgSO4*	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	158000	126	MgSO4	rejected: does not agree with original study	915
Water flea							
Daphnia magna	4	LC50 MOR	760600	607	MgSO4	rejected: does not agree with original study	915
Water flea							
Gambusia affinis	4	MOR	2000000	1596	MgSO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	1	LC50 MOR	3100000	2474	MgSO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	2	LC50 MOR	3100000	2474	MgSO4	rejected: does not agree with original study	508
Mosquitofish							
Gambusia affinis	4	LC50 MOR	3100000	2474	MgSO4	rejected: does not agree with original study	508
Mosquitofish							

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Gambusia affinis Mosquitofish	1	LC50 MOR	15500000	12369	MgSO4	reject: turbid diluent; corrected from orig. ref.	508
Gambusia affinis Mosquitofish	2	LC50 MOR	15500000	12369	MgSO4	reject: turbid diluent; corrected from orig. ref.	508
Gambusia affinis Mosquitofish	4	LC50 MOR	15500000	12369	MgSO4	reject: turbid diluent; corrected from orig. ref.	508
Lepomis macrochirus Bluegill	1	LC50 MOR	3800000	3032	MgSO4	rejected: does not agree with original study	915
Lymnaea sp Pond snail	1	EC50 HAT	2106000	1681	MgSO4	rejected: does not agree with original study	915
Lymnaea sp Pond snail	2	EC50 HAT	1305000	1041	MgSO4	rejected: does not agree with original study	915
Lymnaea sp Pond snail	3	EC50* HAT	1260000	1005	MgSO4*	rejected: does not agree with original study	915
Lymnaea sp Pond snail	4	EC50 HAT	1250000	998	MgSO4	rejected: does not agree with original study	915
Daphnia magna Water flea	1	LC50 MOR	963000	**768**	MgSO4	corrected from original reference	915
Daphnia magna Water flea	2	LC50 MOR	929000	**741**	MgSO4	corrected from original reference	915
Daphnia magna Water flea	3	LC50 MOR	861000	**687**	MgSO4	corrected from original reference	915
Daphnia magna Water flea	4	LC50 MOR	788000	**629**	MgSO4	corrected from original reference	915
Daphnia magna Water flea	4	LC50 MOR	3803000	**3035**	MgSO4	corrected from original reference	915
Lepomis macrochirus Bluegill	1	LC50 MOR	19000000	**15162**	MgSO4	corrected from original reference	915
Lymnaea sp Pond snail	1	EC50 HAT	10530000	**8403**	MgSO4	corrected from original reference	915
Lymnaea sp Pond snail	2	EC50 HAT	6525000	**5207**	MgSO4	corrected from original reference	915
Lymnaea sp Pond snail	2	EC50 HAT	6300000	5027	MgSO4	corrected from original reference	915
Lymnaea sp Pond snail	2	EC50 HAT	6250000	**4988**	MgSO4	corrected from original reference	915
Oryzias latipes	1	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name	Duration	Endpoint/Effect	Conc XSO4	Conc SO4	Test	Comments	Ref No.
Species Common Name	(days)		(ug/L)	(mg/L)	Chemical		see last page
Medaka - high-eyes							
Oryzias latipes	1	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497
Medaka - high-eyes							
Oryzias latipes	1	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497
Medaka - high-eyes							
Oryzias latipes	2	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497
Medaka - high-eyes							
Oryzias latipes	2	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497
Medaka - high-eyes							
Oryzias latipes	2	LC50 MOR >	1000000	798	MgSO4	rejected: reported in orig. ref as Mg ion conc	12497
Medaka - high-eyes							
Plankton	0.17	NR PRP (r=5000-600	5000	4	MgSO4	rejected: tests included Cu, Cd, Ni	8019
Plankton							
Tubifex tubifex	1	EC50 IMM	302790	242	MgSO4	rejected: reported in orig. ref as Mg ion conc	2918
Tubificid worm							
Tubifex tubifex	2	EC50 IMM	164820	132	MgSO4	rejected: reported in orig. ref as Mg ion conc	2918
Tubificid worm							
Tubifex tubifex	4	EC50 IMM	158130	126	MgSO4	rejected: reported in orig. ref as Mg ion conc	2918
Tubificid worm							
Chlorella vulgaris	30	PGR	2012000	**1110**	K2SO4	original reference not checked	8598
Green algae							
Dreissena polymorphia	1	LC50 MOR	112000	62	K2SO4	rejected: Potassium toxic, not the SO4	11011
Zebra mussel							
Fissidens crassipes	7	NR-LETH MOR	150000	**150**	K2SO4	corrected: reported in original study as SO4	7922
Aquatic moss							
Fontinalis antipyretica	7	NR-LETH MOR	100000	**100**	K2SO4	corrected: reported in original study as SO4	7922
Aquatic moss							
Lepomis macrochirus	4	LC50* MOR	3550000	**1959**	K2SO4	original reference not checked	8037
Bluegill							
Leptodictyum riparium	7	NR-LETH MOR >	250000	**250**	K2SO4	corrected: reported in original study as SO4	7922
Aquatic moss							
Leskea polycarpa	7	NR-LETH MOR >	250000	**250**	K2SO4	corrected: reported in original study as SO4	7922
Aquatic moss							
Anguilla anguilla		NR-ENZ		176	K2SO4	rejected: biochem response but no toxic resp.	1, 2
European eel						(test conc. includes diluent SO4 conc. of 76 mg/L)	
Anguilla anguilla		NR-ENZ		176	CaSO4	rejected: biochem response but no toxic resp.	1, 2
European eel						(test conc. includes diluent SO4 conc. of 76 mg/L)	

Table 2: Toxic Effects of Sulphate on Freshwater Organisms

Species Latin Name / Species Common Name	Duration (days)	Endpoint/Effect	Conc XSO4 (ug/L)	Conc SO4 (mg/L)	Test Chemical	Comments	Ref No. see last page
Chlorella vulgaris / Green algae	30	PGR	1872000	**1321**	CaSO4	original reference not checked	8598
Chlorella vulgaris / Green algae	30	PGR	1497000	**1056**	CaSO4	original reference not checked	8598
Gambusia affinis / Mosquitofish	1	LC50 MOR >	56000000	44688	CaSO4	reject: turbid diluent; corrected from orig. ref.	508
Gambusia affinis / Mosquitofish	2	LC50 MOR >	56000000	44688	CaSO4	reject: turbid diluent; corrected from orig. ref.	508
Gambusia affinis / Mosquitofish	4	LC50 MOR >	56000000	44688	CaSO4	reject: turbid diluent; corrected from orig. ref.	508
Lepomis macrochirus / Bluegill	4	MOR	876000	**618**	CaSO4	original reference not checked	8037
Lepomis macrochirus / Bluegill	4	LC50 MOR	2980000	**2102**	CaSO4	original reference not checked	949
Nitzschia linearis	5	LC50 MOR	3200000	**2257**	CaSO4	original reference not checked	949

Bold Text Values = acceptable data

Table 2 AQUIRE Reference Numbers Cross Reference

5052: Kanta, S. and T.A. Sarma. 1980
915: Dowden, B.F. and H.J. Bennett 1965
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2462: Freeman, L. and I. Fowler. 1953
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8037: Trama, F.B. 1954B
9715: Yamane, A.N., M. Okada, and R. Sudo. 1984B
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6631: Khangarot, B.S. and P.K. Ray. 1989
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2918: Khangarot, B.S. 1991
8598: Becker, A.J.Jr. and E.C. Keller,Jr. 1973
11011: Fisher, S.W., P. Stromberg, K.A. Bruner, and L.D. Boulet. 1991
7922: Frahm, J.P. 1975

FIGURES

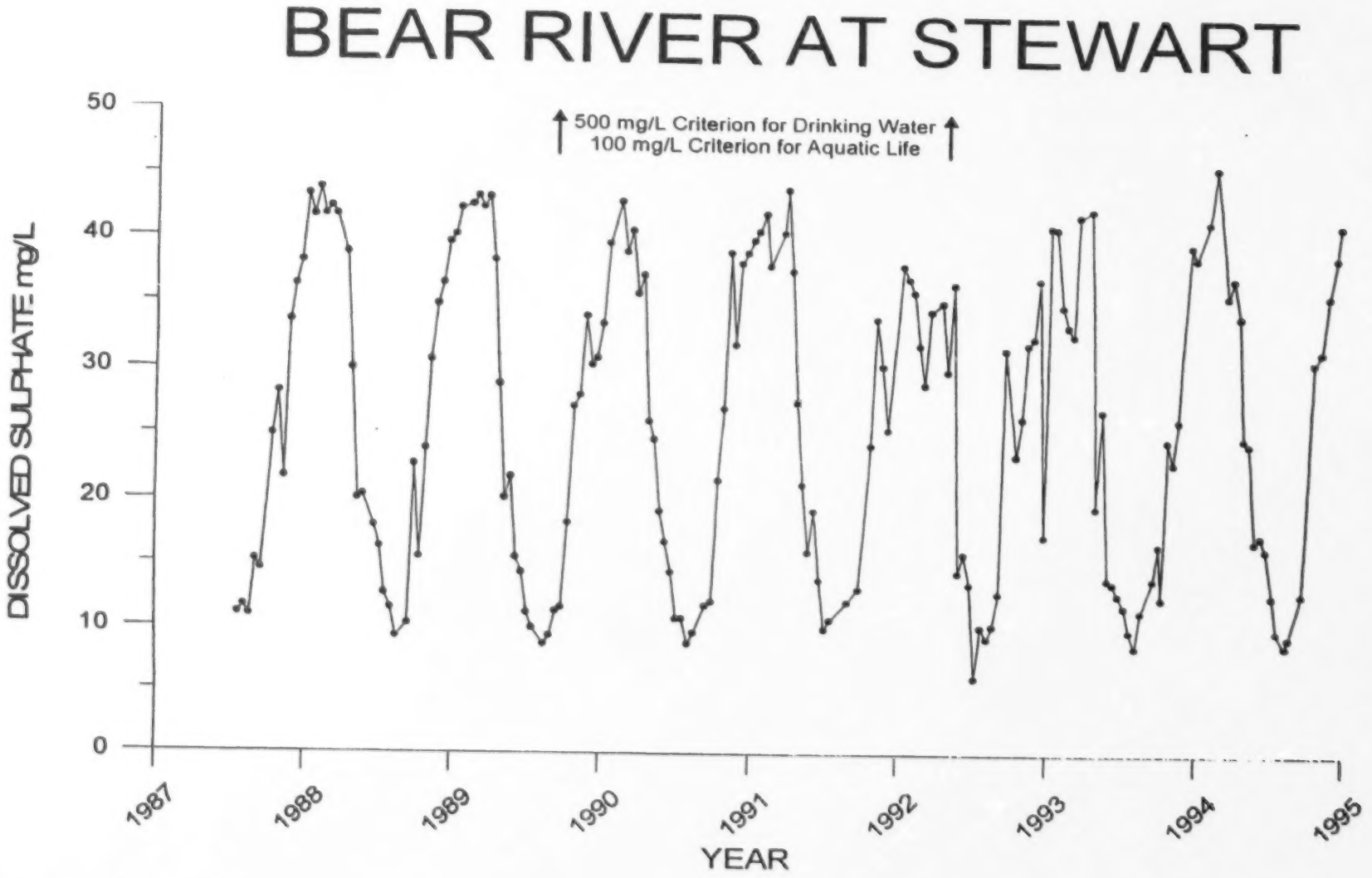

Figure 1 Dissolved Sulphate

Figure 2: Toxicity of Sulphate (SO4) to Freshwater Organisms

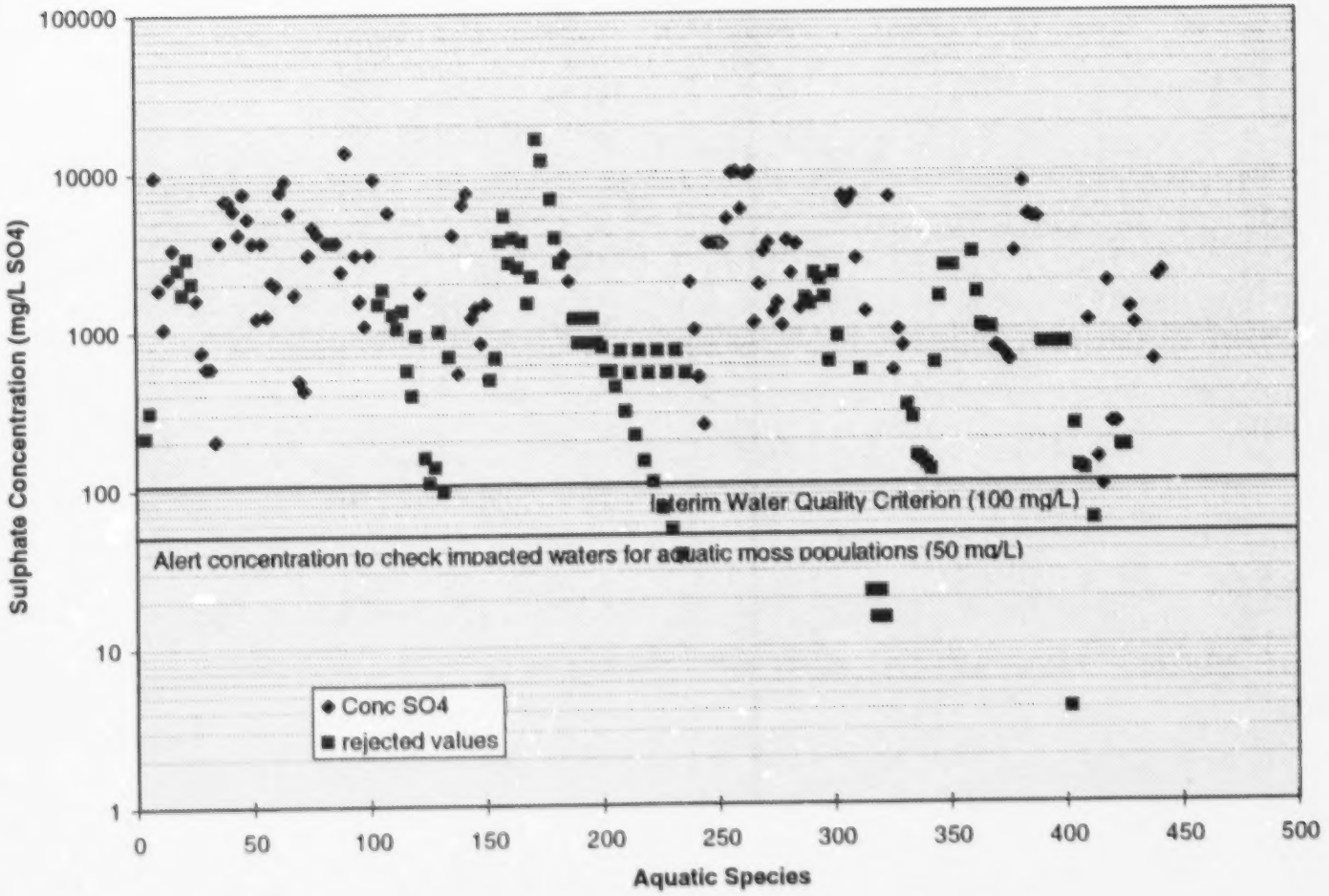

Figure 3: Relationship Between BC MELP Sulphate Toxicity Data and Water Hardness